

A photometric and spectroscopic study of WW And - an Algol-type, long period binary system with an accretion disc

Michał Siwak^{☆a}, Stanisław Zola^{a,b}, Tomasz Szymanski^a, Maria Kurpinska-Winiarska^a, Maciej Winiarski^{a,b}, Dorota Koziel-Wierzbowska^a, Wacław Waniak^a, Michał Drahus^c

^a*Astronomical Observatory, Jagiellonian University, ul. Orla 171, 30-244 Kraków, Poland,*

^b*Mount Suhora Astronomical Observatory, Cracov Pedagogical University, ul. Pochorążych 2, 30-084 Kraków, Poland*

^c*Department of Earth and Space Sciences, University of California at Los Angeles, 595 Charles E. Young Dr. E., 3711 Geology, Los Angeles, CA 90095-1567*

Abstract

We have analyzed the available spectra of WW And and for the first time obtained a reasonably well defined radial velocity curve of the primary star. Combined with the available radial velocity curve of the secondary component, these data led to the first determination of the spectroscopic mass ratio of the system at $q_{\text{spec}} = 0.16 \pm 0.03$. We also determined the radius of the accretion disc from analysis of the double-peaked H_α emission lines. Our new, high-precision, Johnson *VRI* and the previously-available Strömgren *vby* light curves were modelled with stellar and accretion disc models. A consistent model for WW And – a semidetached system harbouring an accretion disc which is optically thick in its inner region, but optically thin in the outer parts – agrees well with both spectroscopic and photometric data.

Keywords: Stars: binaries: eclipsing, stars: mass-loss, stars: individual: WW And, accretion: accretion discs

1. Introduction

WW And ($V = 10.9 \text{ mag}$, $B-V = 0.49 \pm 0.09$, A5+F3p) is a long period ($P_{\text{orb}} \approx 23.3 \text{ d}$), Algol-type binary system. The first spectroscopic data obtained in the blue part of the spectrum at orbital phases close to the primary minimum revealed red emission components in hydrogen and the Ca II K absorption lines (Wyse, 1934; Struve, 1946), and suggested the existence of H_α and H_β emission. As the source of the emission they proposed circumstellar matter lost by the Roche lobe filling secondary star and accreted by the primary component through the first Lagrangian point. Due to the considerable contamination of these lines by the circumstellar matter, the radial velocity curve of the primary star remained undefined (Struve, 1946).

Direct evidence for an accretion disc surrounding the primary, mass-gaining, component came with the discovery of double-peaked H_α emission line (Olson & Etzel, 1993). A more detailed analysis of the line profile reveals that changes of the equivalent width (EW) of its violet and red emission components with orbital phase can be explained by enhanced emission from the stream-impact region localized in the accretion disc (Olson & Etzel, 1995). An additional argument for the presence of a large accretion disc follows from analysis of EW changes of the O I 7774 absorption line over the orbital period (Etzel et al., 1995).

The first photometric light curves of WW And in *wby*-Strömgren and *I*-Kron filters were obtained by

Olson & Etzel (1993). They made an attempt to model the light curves with the Wilson-Devinney (WD) light curve synthesis code (Wilson, 1979), assuming a semidetached configuration. However, a significantly better fit was obtained for a detached geometry, with the secondary component filling about 93% of its Roche lobe. The above-mentioned arguments indicating the presence of an accretion disc around the primary component led the authors to conclude that mass loss from the secondary star occurs through the stellar wind rather than Roche lobe overflow. Zola (1997) modelled the WW And *vbyI* light curves assuming a semidetached configuration and using a modified WD code accounting for effects introduced by an accretion disc around the primary component. A reasonable fit was obtained but the disc radius was smaller than 0.1 of the orbital separation and the solution was not unique – the fit was almost equally good for a range of photometric mass ratio values.

In order to get a definitive answer about the configuration of this system and obtain more accurate properties of the accretion disc from light curve modelling, we decided to obtain new, high-quality photometric data especially at phases around the secondary minimum. To minimize the scatter due to accretion effects observed in many other mass transferring Algol-type binary systems, a large effort was made to collect a complete light curve in Johnson *BVRI* filters in as short a time as possible. We describe the new photometric data in Section 2 and compare the new Johnson *V* and the older Strömgren *y* light curves in order to check for possible changes of the primary mini-

[☆]e-mail: siwak@oa.uj.edu.pl

imum depth. In Section 3 we present the results obtained from analysis of the spectroscopic data – the spectroscopic mass ratio (determined for the first time) and the size of the accretion disc radius. Models obtained from *vbyVRI* light curve modelling are presented in Section 4. We summarize the results in Section 5.

2. Observations and data reduction

We observed WW And with the 50 cm Carl Zeiss telescope at the *Fort Skala* Astronomical Observatory of the Jagiellonian University. This telescope was equipped with a Photometrics S300 CCD camera with the SITe SI003B, 1024x1024-pixel chip and a set of broadband Johnson-Bessell *UBVRI* filters, manufactured by Custom Scientific. With the 6.7 m focal length of this telescope, the field of view was 12'x12'.

The data were collected during 86 nights over 4 consecutive seasons in *BVRI* filters. The first observations were obtained on 4/5th January, 2002, while the latest ones on 21/22 October, 2005. They were reduced for *bias*, *dark* and *flatfield* in the usual way using our scripts working under the *ESO-MIDAS* software environment. The aperture photometry was made making use of *DAOPHOT II* package (Stetson, 1987). GSC 3638-01674 (having almost the same colour index as the variable star) served as the comparison, while GSC 3638-01421 and GSC 3638-01742 as the check stars. No night-to-night variations larger than 0.01 mag (σ) were noticed in the *comparison-check* star differential photometry in all filters. Due to the small angular separation between the variable, comparison and check stars, the corrections for differential atmospheric extinction k turned out to be negligible over the entire range of observed airmasses. The data obtained in the *B* filter were also corrected for colour extinction β using the mean coefficient obtained for the *Fort Skala* Observatory by Winiarski (private communication). As a result, we obtained a good quality light curves with a formal scatter of the individual points of a few milimagnitudes. As the secondary minimum was observed several times it is much better covered than in the *uvbyI* light curves obtained by Olson & Etzel (1993). The new data show a scatter whose amplitude grows toward shorter wavelengths, reaching almost 0.02 mag in the *B* filter. An analogous trend is also visible in the *uvbyI* light curves (Olson & Etzel, 1993). The data were left in the instrumental system and the phases were calculated using the most recent linear elements provided by J.M. Kreiner (Kreiner, 2004):

$$HJD = 2,453,665.502(23) + E \times 23.28525(3), \quad (1)$$

where E is an epoch number.

According to visual observations made at the beginning of the 20th century and presented by Leiner (1927), the primary minimum of WW And, lasting about 0.07 P_{orb} , was total and nearly 1.1 mag deep. As the Strömgren *y*-band data clearly shows a shorter (0.05 P_{orb}), partial,

Table 1: Radial velocities of both components (RV_1 - primary, RV_2 - secondary) obtained by means of the Broadening Function method from spectra obtained by Olson & Etzel (1993) in the Mg II 4481Å region. The accuracy of individual data points is no worse than 5 km/s (see Sec. 3.1).

HJD-2,448,000	phase	RV_1 [km/s]	RV_2 [km/s]
456.83665	0.3107	-37.4	68.7
456.86443	0.3119	-31.0	64.9
458.88888	0.3989	-28.9	40.6
851.75641	0.2708	-25.9	81.9
851.79452	0.2725	-24.5	80.2
886.95239	0.7823	-2.3	-102.5
1180.89606	0.4060	-21.7	46.3

0.6 mag deep primary eclipse, Olson & Etzel (1993) proposed that perhaps WW And continuously changes its orbital inclination. However, Meyer (2005) re-analyzed Leiner's data and gave a strong proof that the depth of minimum given by Leiner was erroneous and most probably the suggested change of inclination is not taking place. In order to check the above hypothesis by means of more uniform data set, we compared the Olson's *y* and our *V* light curves, obtained 15–20 years later. We found that primary minimum in our new *V* data is only 0.02 mag deeper than that in the *y* filter. Such a small difference can be fully explained by combination of small changes in the circumbinary environment and the lack of transformation between the *V* and *y* bands.

3. Analysis of spectroscopic data

3.1. Radial velocity determination

In Figure 1 we present four Broadening Functions (BF) calculated from the medium resolution (0.2Å/pix) spectra obtained by Olson & Etzel (1993) in the Mg II 4481Å region. These reveal the sharp, well defined profile of the secondary component (as expected in the case of synchronous rotation and the long orbital period) and the broad profile of the primary star. Due to the poor velocity sampling of the BF profiles (13 $km\ s^{-1}$) they cannot be studied in greater details; this would require high-resolution spectra.

We attempted to fit the broad, triangular profiles of the primary with rotationally broadened synthetic profiles, but failed. A similar problem was encountered by Pribulla & Rucinski (2008) for the primary component of the close binary AW UMa. Therefore, we tentatively propose that this shape of the profile is caused by the fast rotating, optically thick inner part of an accretion disc, rather than by close-to-critical rotation of the primary component, as proposed by Olson & Etzel (1993). In Figure 1 we also notice that the BF profile of the primary component obtained at phase 0.782 is asymmetric, i.e. its maximum intensity is considerably shifted to smaller velocities. This may be explained by combination of effects

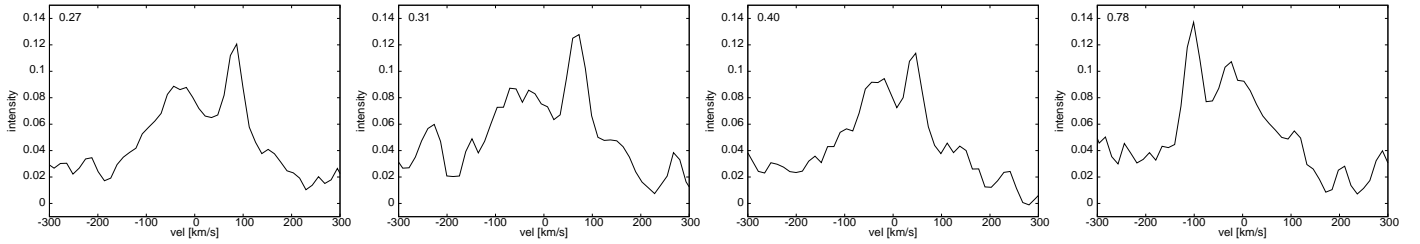


Figure 1: Broadening Functions obtained from spectra obtained in Mg II 4481 Å region in different orbital phases, indicated in plots.

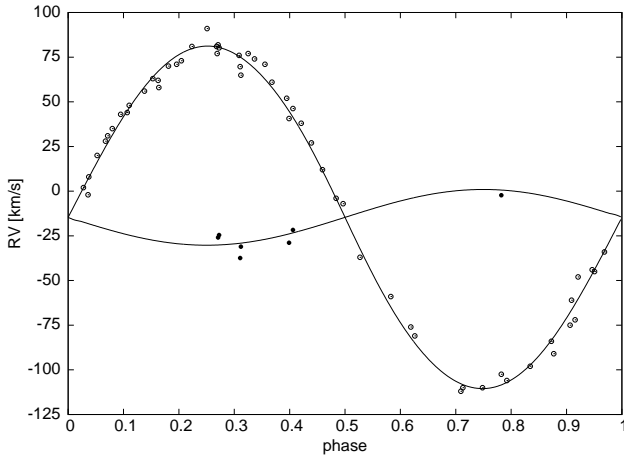


Figure 2: The radial velocity curves of WW And and the fit obtained with the WD code assuming a stellar model.

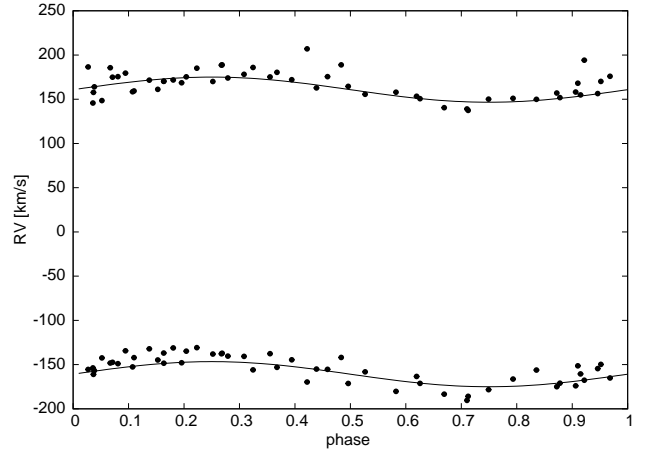


Figure 3: Measured radial velocities of the H α blue and red peaks (points). Also shown the model for assumed keplerian rotation of a circular disc (continuous lines).

introduced by a non-uniform flux distribution of the inner parts of the accretion disc, and/or by radiation from a hot spot produced by a stream-disc interaction, which is expected to be best visible at the second quadrature.

From measurements of the *light centroids* of the BF profiles we obtained seven new radial velocity points for each component (Table 1). Despite their uncertainty ($\approx 5 \text{ km/s}$) related to limited instrument stability (Olson, private communication), they provide the first reasonably well defined radial velocity curve of the primary component (Fig. 2). We appended our measurements to the data of the secondary component obtained from the iron lines in the H α region (Olson & Etzel, 1993) and as the result we obtained the spectroscopic value of the mass ratio, $q_{\text{spec}} = M_2/M_1 = 0.16 \pm 0.03$. This value is small enough to avoid direct stream impact on the primary component photosphere; instead the stream is expected to encircle the primary star and to form an accretion disc (Lubow & Shu, 1975).

3.2. Disc radius determination

The size of an accretion disc can be determined from separation of the blue and red peaks of the H α emission line (Smak, 1981). Therefore the H α spectra obtained by Olson & Etzel (1993) have been transformed into velocity space, accounting for the mean system velocity. While measuring the velocities of both peaks (Fig. 3) it turned

out that they are also contaminated by an absorption feature. We measured the radial velocities of this absorption line and found that they follow the RV curve of the secondary component. Based on this result we identify this as the H α line originating in the secondary. The derived size of the accretion disc as a function of inclination is given in Table 2, while the synthetic profiles at four orbital phases are shown in Fig. 4.

Table 2: Circular disc radius as a function of inclination (in units of component separation).

inclination	disc radius
90	0.443
88	0.442
86	0.440
84	0.438
82	0.434
80	0.430
78	0.423
76	0.417
74	0.409

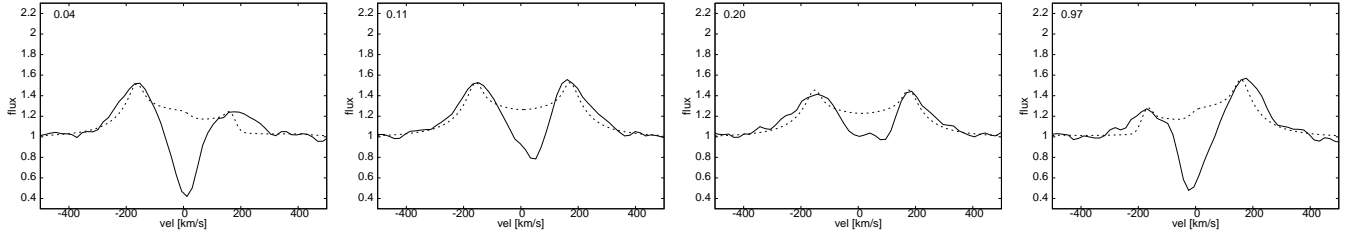


Figure 4: Comparison of the H_α line theoretical profiles (dotted line) with observations (continuous line). The phases are indicated in plots.

4. Light curve modelling

Due to significant scatter and seasonal effects visible in the B data, this light curve was discarded from the light curve modelling. From the original VRI data we calculated 140, 147, and 149 mean points, respectively and 145 mean points were calculated for each of the Strömgren vby filters. The $vbyVRI$ data, converted into flux units and normalized to about unity at the phase 0.25, were then simultaneously modelled by means of the stellar and the accretion disc models.

4.1. Stellar model

As the first step we modelled the $vbyVRI$ light curves using the 1996 version of the WD code extended with the Monte Carlo method as a global minimum search procedure (Zola et al., 1997, 2010). This was aimed at checking the system configuration, which in our code is not assumed *a priori* but is obtained as a result. We also wanted to check how good the fit could be for the new, more accurate data within a model not accounting for the presence of an accretion disc in the system.

Based on the A5 spectral classification obtained by Struve (1946), and the *spectral type – effective temperature* calibration for Main Sequence stars (Harmanec, 1988), we assumed 8150 K as the effective temperature of the primary star T_{eff}^{prim} . We also computed a second model for $T_{eff}^{prim}=9500$ K, as inferred by Olson & Etzel (1993) from the colour change at the primary minimum. The spectroscopic mass ratio, $q_{spec} = 0.16$ (Section 3.1), was assumed, as a constant parameter. Theoretical values of albedo and limb darkening coefficients were adopted: $A_1 = 1$, $g_1 = 1$ for the radiative primary (von Ziepel, 1924), and $A_2 = 0.5$, $g_2 = 0.32$ for the convective secondary star (Lucy, 1967; Rucinski, 1969). We used the square root limb-darkening law, with respective coefficients from the Claret et al. (1995) and Díaz-Cordovés et al. (1995) tables, applied as a function of the wavelength and effective temperature of the star. A simple analytical model of the reflection effect ($mref = 1, nref = 1$) was used during all computations. We assumed the stars rotate synchronously. We adjusted orbital inclination i , temperature of the secondary component T_{eff}^{sec} , potentials $\Omega_{1,2}$ and luminosity L_1 (in the WD code notation) of the primary component. The

Table 3: The best-fit values obtained from light curve modelling within the stellar and the accretion disc models. The errors are given in parentheses. The accretion disc temperature T_d did not converge to any specific value.

Parameter: * - fixed, ** - computed

parameter	stellar model	disc model
$i[^\circ]$	79.90 (1)	76.92 (11)
$T_{eff}^{prim}[K]$	8150*	8150*
$T_{eff}^{sec}[K]$	4135 (1)	4500*
Ω_1	28.08 (5)	16.44 (67)
Ω_2	2.2330 (6)	2.1300**
q_{spec}	0.16*	0.16*
L_{1v}	7.420 (14)	2.04 (1.65)
L_{1b}	6.531 (13)	3.11 (1.45)
L_{1y}	5.343 (11)	3.63 (1.21)
L_{1V}	5.259 (11)	3.46 (0.81)
L_{1R}	4.098 (10)	3.67 (0.61)
L_{1I}	2.742 (07)	3.18 (0.41)
L_{2v}	5.187**	1.11**
L_{2b}	5.888**	2.13**
L_{2y}	6.965**	3.39**
L_{2V}	6.943**	3.26**
L_{2R}	7.978**	4.83**
L_{2I}	9.176**	6.66**
l_{dv}	—	0.771 (163)
l_{db}	—	0.615 (160)
l_{dy}	—	0.482 (157)
l_{dV}	—	0.495 (105)
l_{dR}	—	0.357 (92)
l_{dI}	—	0.241 (79)
r_d	—	0.084 (8)
T_d	—	not conv.
γ	—	1.0*
β	—	6.2 (3.3)
$\chi_{red,w}^2$	5.153	3.023

IPB control parameter was set to 0, therefore the luminosity of the secondary (L_2) was calculated as a function of temperatures, L_1 , and the system geometry.

The solutions converged for both models, the one with higher (9500 K) temperature of the primary component gave a somewhat better fit. The parameters obtained within the Roche model are given in Table 3, while the theoretical light curves along with observed ones are shown in Fig. 5 (corresponding to the model with $T_{eff}^{prim} = 8150$ K, see Sec. 5 for explanation). The theoretical light curves in the V and y filters fit the data best – in other filters discrepancy with observations is larger, the secondary minimum being too shallow in longer wavelengths (R and I), while too deep in v and b filters. The shape of the primary minimum is too shallow both in short and in long wavelengths. The ellipticity effect of the theoretical light curves roughly corresponds to that observed but, to achieve this, the resulting system configuration is detached with the primary star being well within its Roche lobe and the secondary component almost filling in its Roche lobe ($\Omega_2 = 2.2330$ while $\Omega_{Roche} = 2.12996$). The solution could be further improved only by adding more free parameters; in order to obtain a better fit in the primary minimum, Olson & Etzel (1993) considered over synchronous rotation of the primary star.

4.2. An accretion disc model

As the next step, our goal was to derive a model consistent with all properties of WW And, inferred both from the photometric and the spectroscopic data. Therefore, we applied the modified WD code which accounts for effects caused by a circular accretion disc surrounding the primary component (Zola 1991, and references therein). The disc thickness grows linearly with radius, it is assumed to be optically thick and radiate as a black body. This model has already been successfully applied to solve the light curves of some long-period Algol-type and W Serpentis-type binary systems (Zola & Ogloza 2001, and references therein). As mentioned in Section 1, the first, moderately successful attempt to fit the *vbyI* light curves of WW And using this code was published by Zola (1997). The solution reasonably described the observed light curves for the photometric mass ratio $q = 0.20$, but computations resulted in a very small disc radius $r_d = 0.06$ (in units of component separation).

Similarly to the stellar model, we performed computations for two effective temperatures of the primary, mass accreting star: 9500 K and 8150 K. We kept the mass ratio fixed at its spectroscopic value (see Sec. 3.1) and a semidetached configuration was assumed, thus naturally providing matter for the accretion disc. Furthermore, the disc radius was not adjusted but its value was chosen according to the orbital inclination as derived from the separation of blue and red peaks (Tab. 2). The orbital inclination i , potential of the primary component Ω_1 , disc luminosity l_d and temperature T_d , β – the parameter describing the vertical disc thickness $z(r) = r \tan \beta$, luminosity of the

primary L_1 and the effective temperature of the secondary star were adjusted in this step.

Models obtained for the two assumed temperatures of the primary star both gave rather poor fits (as indicated by $\chi_{red,w}^2$). The theoretical light curves showed too high ellipsoidal effects and an unacceptable, too deep secondary minimum, poorly resembling the data in all filters. The models also resulted in a cool secondary star ($T_{eff}^{sec} = 3800$ K) and a negligible disc flux contribution in all filters except V and R , where it reached 5% and 13% of the total system flux, respectively.

This first approach gave us some hints about how to proceed further. The assumed semidetached configuration caused higher than observed ellipsoidal effects, therefore the search procedure kept choosing a lower and lower temperature of the secondary star to minimize these effects and eventually hit the lower search limit. As argued by Olson & Etzel (1993), the secondary star cannot have such a low temperature and, as a consequence, the temperature of the mass-losing star was fixed at $T_{eff}^{sec} = 4500$ K, estimated from colour variations during the primary eclipse by Olson & Etzel (1993). Examination of the shape of the theoretical light curves around the secondary eclipse (where the disc obscures the mass losing star) revealed that if the disc was optically thick, its size was too big. In subsequent computations we added the disc radius to the list of adjusted parameters but kept the secondary star temperature fixed, thus the number of free parameters remained the same as in the previous step.

With the new setup, both sets of computations resulted in much better solutions. Due to higher disc light contributions, the theoretical light curves fit the primary minimum very well in all filters, also the ellipsoidal effect agrees with that observed (see Fig. 5). However, the solutions, independent of the assumed primary star temperature, converged at a small disc radius value – 0.08-0.09 (in separation units) – which agrees with the result of Zola (1997) but contradicts the disc size obtained from the H_α line red and blue peak separation measurements (Sec. 3.2). Based on the above results we can draw the conclusion that, in order to fulfill the observed properties, the accretion disc in WW And must be partly optically thin, with only the inner parts being optically thick (Fig. 6). Since our model assumes only an optically thick accretion discs, it cannot fully account for this case. Another problem encountered by the thick disc model is the very high disc light contribution in the v -filter – more than 75% of the total system flux.

5. Discussion and Conclusions

We gathered new *BVRI* light curves of the Algol-type binary system WW And, covering the entire orbital period and revealing for the first time the very well-defined shape of a grazing secondary minimum. The Broadening Function method applied to the archival spectra allowed

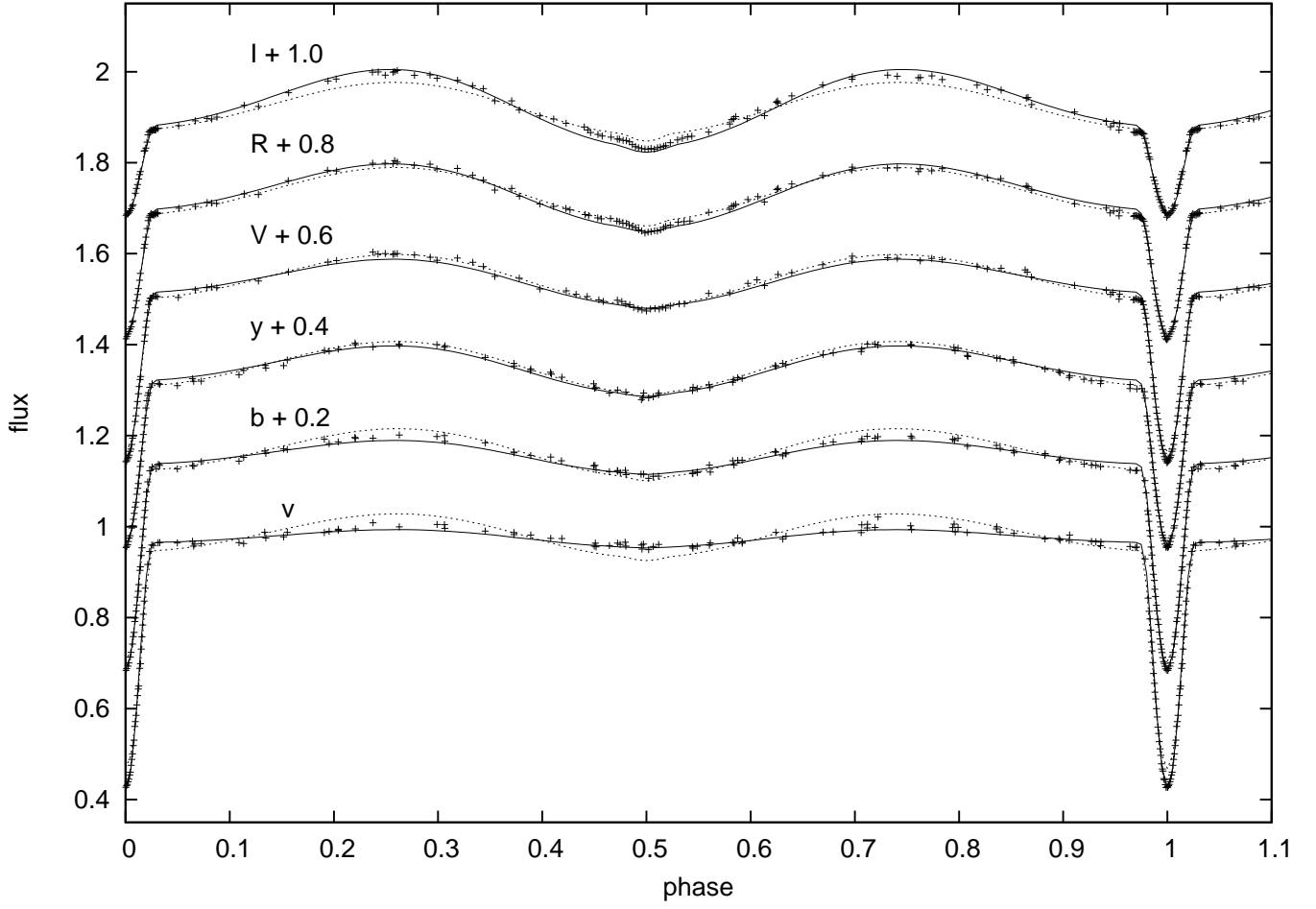


Figure 5: The comparison between the observed (+) and synthetic light curves obtained from the stellar (dotted lines) and the disc models (continuous lines) assuming the primary temperature $T_{eff} = 8150$ K.

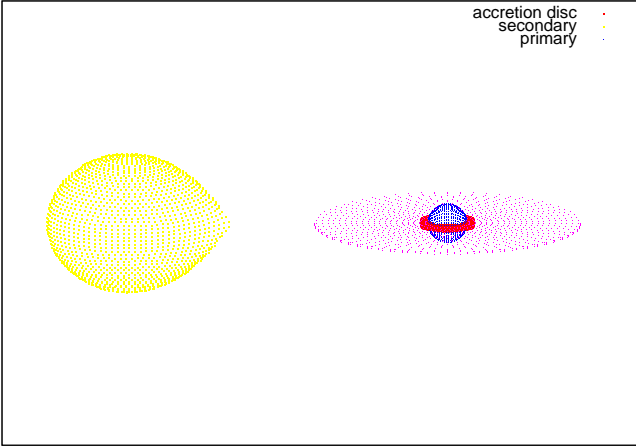


Figure 6: The view of the model of WW And as seen at the phase=0.25. The secondary fills in its Roche lobe while the primary component is surrounded by an accretion disc. The inner part of the disc (a ring close to the primary), up to the radius of 0.084 is optically thick while the outer region is optically thin. We made no attempt to reproduce the vertical thickness of the optically thin region, it is shown only for displaying the entire disc size as indicated by the double peaked emission lines.

detection of the radial velocities of the primary star and estimate the system mass ratio as $q_{spec} = 0.16 \pm 0.03$.

The new light curves in the *VRI* wide band filters, along with the Strömgren *vby* filters published several years ago, have been modelled assuming both a stellar-only model and another one accounting for the presence of an accretion disc in the system. The solution derived with the stellar model confirmed the results published by Olson & Etzel (1993) – in order to obtain an acceptable fit, the system configuration must be detached. This excludes the possibility of mass transfer through the L_1 point as the source of matter for the disc manifesting itself by the double-peaked hydrogen lines visible at all phases. Our second approach, the application of a model accounting for disc effects (partial obscuration of the mass-gaining star, eclipsing of the mass-losing star by the disc, and the disc light contribution) and a semidetached configuration also produced a reasonable fit to the observed light curves.

Unexpected disc properties have been deduced. In order to fit the photometric and spectroscopic data, only the inner parts of the disc could be optically thick. The outer parts, from the radius of about 0.08 to the disc edge, must be optically thin to fit the shape of the light curve near the secondary minimum. The disc light contribution needed to reflect the observed ellipsoidal effects is high, especially in the Strömgren *v* filter where it reaches more than 75 percent. Such a high value, if it is not a numerical artifact – it is very hard (if at all possible) to disentangle the primary star light from that of the disc – is not justified when one compares the emitting surfaces of the disc and the stellar components. However, an additional contribution could be possible due to an optically thin outer disc region: emission in the Balmer lines and in the boundary layer

visible at such a low inclination and relatively low disc thickness.

We performed computations for two temperatures of the primary star: 8150 K and 9500 K. However, despite obtaining a slightly better fit for the higher T_{eff}^{prim} value with the stellar model (with the disc model both temperatures provided equally good fits), we consider the lower temperature to be more probable and present solutions for $T_{eff}^{prim}=8150$ K (Table 3). This is for two reasons: (1) this value follows from the spectral classification and (more importantly), (2) only for this temperature can the spectrum of the primary star contain strong absorption lines in the Mg II 4481Å region, allowing for determination of its radial velocities (described in Sec. 3.1).

We conclude that the disc model better explains the observed properties of WW And. Our results indicate that it consists of two stars having the following parameters derived from the combined spectroscopic and photometric data: the mass-gaining component, belonging to the Main Sequence ($R_1 \approx 3.25R_\odot$, $M_1 = 3.18 \pm 0.09M_\odot$), and the mass-losing star – separated by $53.0 \pm 0.5R_\odot$ – being a giant ($R_2 \approx 12.47R_\odot$, $M_2 = 0.51 \pm 0.09M_\odot$). The cooler star fills its Roche lobe, providing matter through the L_1 point at rather low rate to the disc surrounding the smaller, hotter star. As the result, the disc has no stationary structure; instead, its outer parts are optically thin while the innermost region is optically thick. These inner, fast rotating parts of the disc could broaden the profile of the primary component seen in the Broadening Functions and in the spectra.

Further progress on understanding this system can be obtained from detailed studies of the H_α and other Balmer emission lines, and from high-resolution spectra analyzed by means of the BF method. This would provide more precise radial velocities of the primary component, necessary to improve the preliminary value of the spectroscopic mass ratio, and allow for detailed studies of the accretion disc structure. The latter task will require modification of the disc model, as in its present form it can only be applied to a fully optically thick and circular disc, while an eccentric accretion disc could explain the asymmetries visible in the *VRI* light curves around the secondary minimum and between the first and the second quadratures.

Acknowledgments

We gratefully acknowledge Prof. Ed Olson and Dr. Paul Etzel for kindly provided spectra of WW And, the anonymous referee for the very important comments and suggestions, and Dr. Greg Stachowski for language corrections. MS acknowledges the Canadian Space Agency Post-Doctoral position grant to Prof. Slavek M. Rucinski within the framework of the Space Science Enhancement Program.

References

- Claret A., Díaz-Cordovés J., Giménez A., 1995, A&AS, 114, 247
Díaz-Cordovés J., Claret A., Giménez A., 1995, A&AS, 110, 329
Etzel P. B., Olson E. C., Senay M. C., 1995, AJ, 109, 1269
Harmanec P., 1988, BAICz, 39, 329
Kreiner J. M., 2004, AcA, 54, 207
Leiner E., 1927, AN, Band 229, Nr. 5487
Lubow S. H., Shu F. M., 1975, ApJ, 198, 383
Lucy L. B., 1967, Zeitschrift für Astrophysik, 65, 89
Meyer R., 2005, *Open European Journal on Variable Stars*, vol. 0008, p.1
Olson E. C., Etzel P. B., 1993, AJ, 106, 759
Olson E. C., Etzel P. B., 1995, AJ, 109, 1308
Pribulla T., Rucinski S. M., 2008, MNRAS, 386, 377
Rucinski S. M., 1969, AcA, 19, 245
Smak J. I., 1981, AcA, 31, 395
Stetson P. B., 1987, PASP, 99, 191
Struve O., 1946, ApJ, 103, 76
Wilson R. E., 1979, ApJ, 234, 1054
Wyse A. B., 1934, *Lick Observatory Bulletin*, 17, 37
Von Ziepel H., 1924, MNRAS, 84, 665
Zola S., 1991, AcA, 41, 213
Zola S., Kolonko M., Szczech M., 1997, A&A, 324, 1010
Zola S., 1997, IAUJ 8, 49, *Stellar Evolution in Real Time, 23rd meeting of the IAU, Joint Discussion 8, 22-23 August 1997, Kyoto, Japan*
Zola S., Ogloza W., 2001, A&A, 368, 932,
Zola S., Gazeas K., Kreiner J. M., et al., 2010, MNRAS, 408, 464